Google AI Quantum

Superconducting Integrated Circuits for QC

Ofer Naaman

Workshop on Cryogenic Electronics
Fermi National Lab 6/20/19

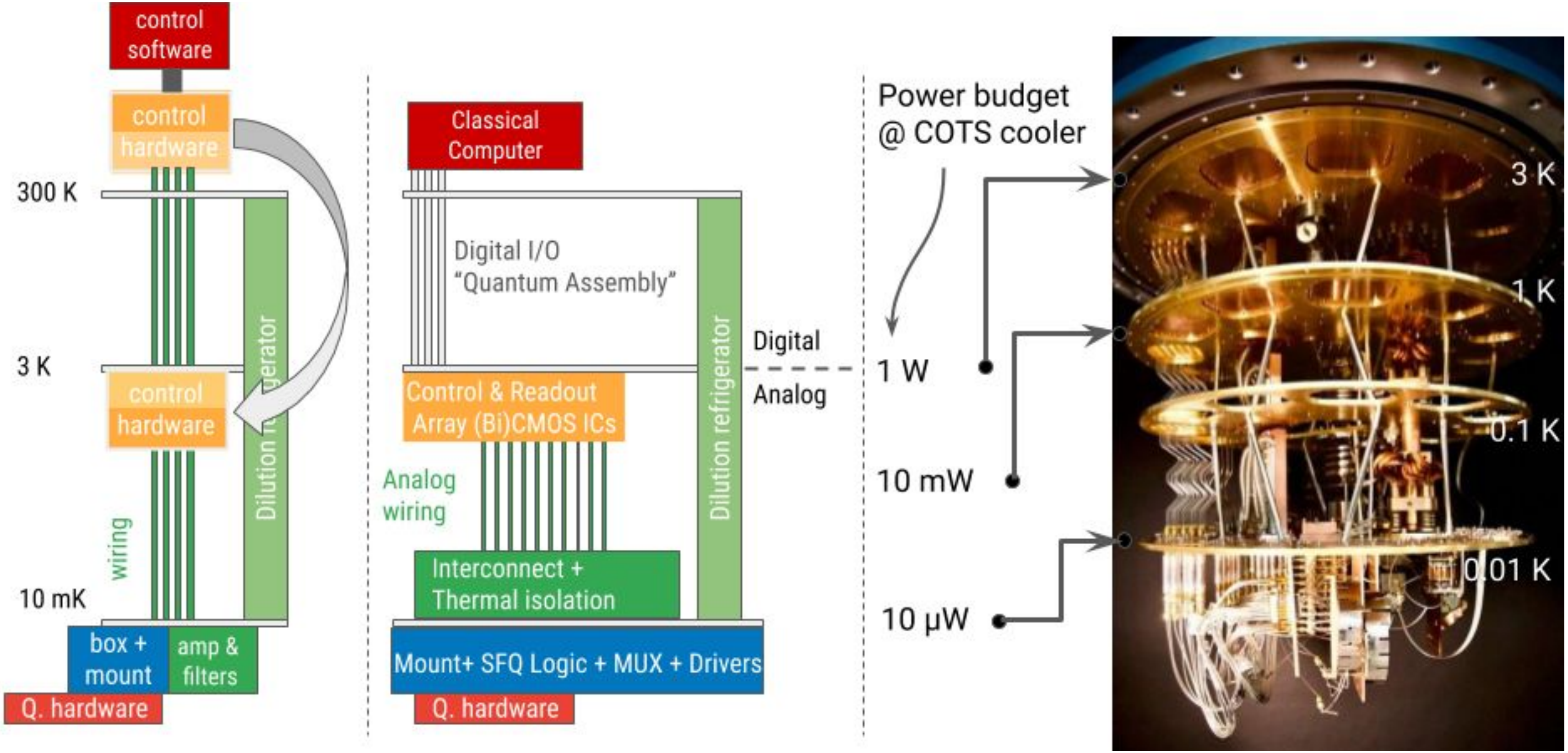
Near Term Gaps

- Wiring
- Signal integrity
- Passives
- Amplifiers

Long Term Solutions

- Reduce I/O
- Cryogenic control - CMOS and SC
- Superconducting μwave components

Scale by Integrating Control Electronics



Agenda

- Aspects of superconducting IC design
  - Lossless wiring
  - Active devices - Josephson junctions

- Design examples
  - Microwave switches
  - Mixers and modulators
  - Amplifiers and circulators

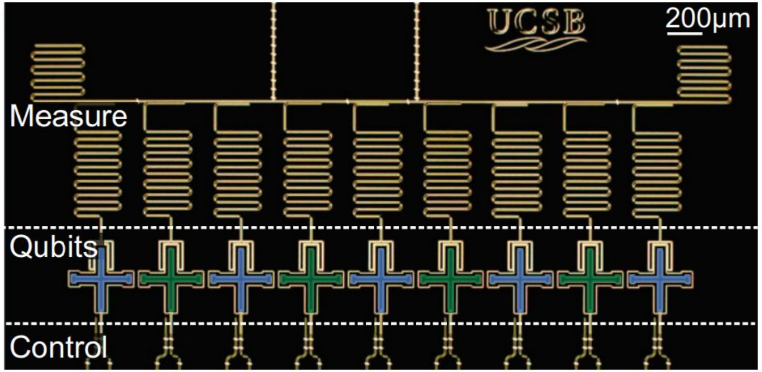
Aspects of Superconducting IC Design

Superconductors are Lossless

Implication:

- Can use long, sub-micron wiring (eg. spiral inductor) at microwave frequencies.
- Compact transmission-line resonators with Q > 1M

But: watch for high Q parasitic resonances!



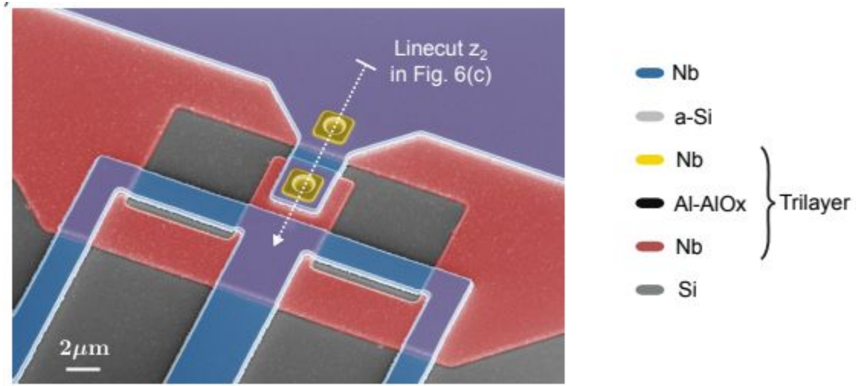
Superconductors are Lossless

Implication:

- Transformers work at DC

$$\begin{array}{c} \mathbf{V} = -i\omega\hat{L}\mathbf{I} \\ \Downarrow \\ \mathbf{\Phi} = \hat{L}\mathbf{I} \end{array}$$

where Φ is the flux $\quad \Phi = \int V\,dt$



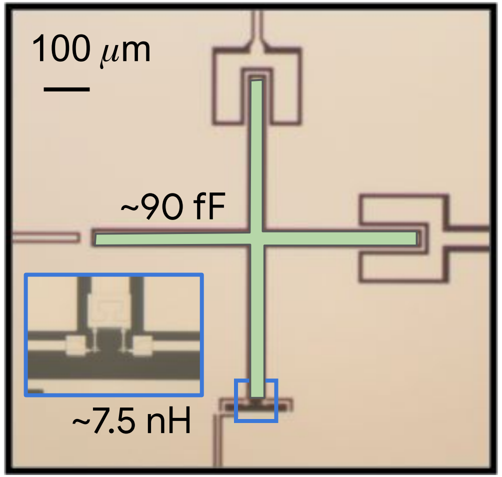
NIST- F. Lecocq, Phys. Rev. Applied (2017)

But:

- Stray magnetic fields generate DC current as well
- Every SC loop can trap flux

Active Devices: Josephson Junctions

- Tunnel junction between superconductors
- Critical current $I_c \propto$ area
  - 10's nA - μA in qubit circuits
  - μA - 100's μA in microwave and logic circuits

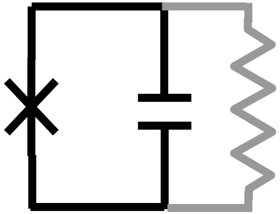


Lots of lossless inductance in small space

- When $I < I_c$: lossless nonlinear inductor

$$L_J = \frac{\hbar}{2eI_c\cos\delta}, \qquad \delta = \sin^{-1}(I/I_c) \qquad 1\,\mu\text{A} \longrightarrow 329\text{ pH}$$

- Inductance is tunable if we control the current
  - Two junctions in parallel: DC SQUID
  - One junction in parallel with inductor: RF SQUID



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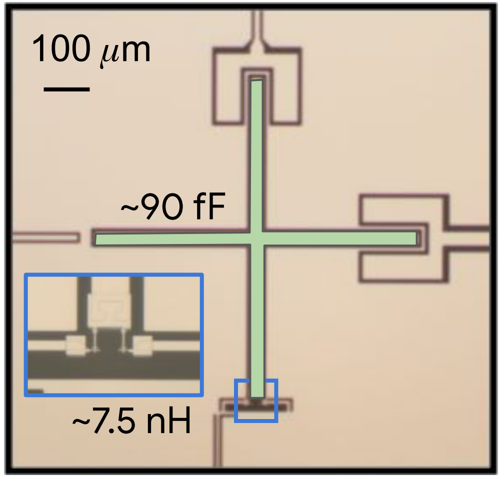

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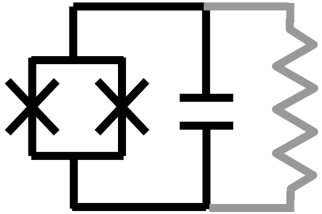

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- Critical current I_c ∝ area
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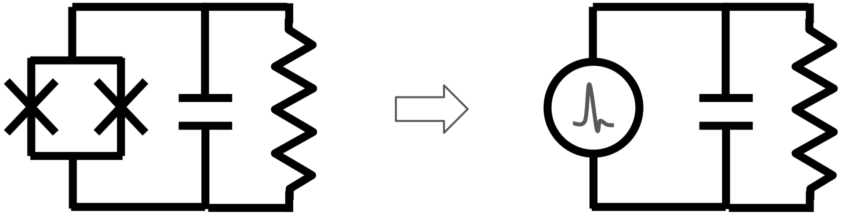
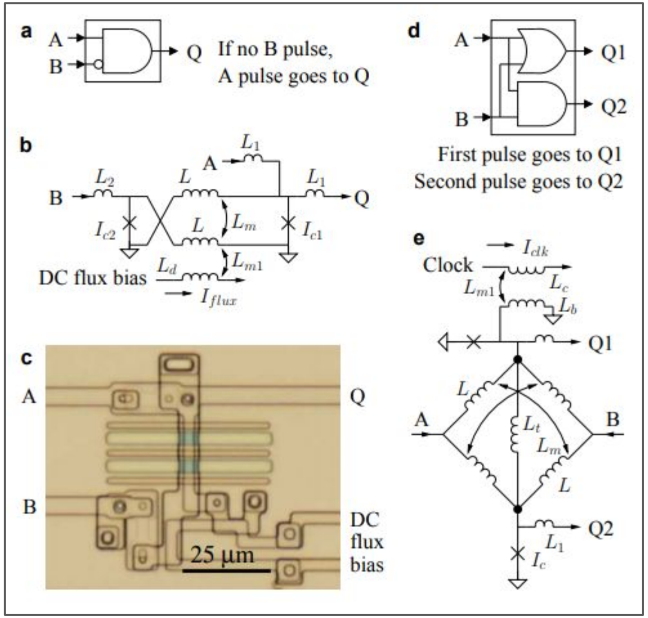
- When $I > I_c$:
  - dissipative current through shunt resistance
  - JJ is a pulsed voltage source - used for SFQ logic
  - SFQ pulse area 2mV × 1 ps - fast and quantum accurate





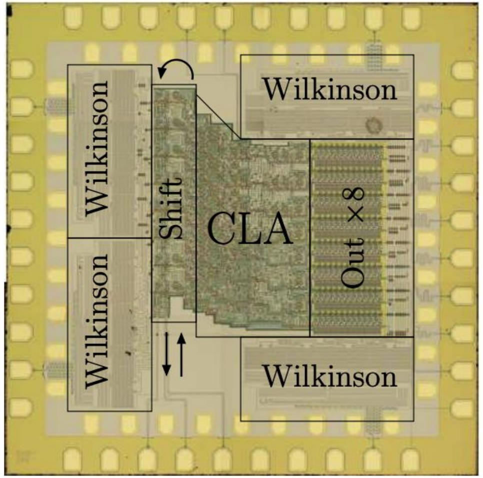
Herr, J. Appl. Phys. (2011)

More on digital and SFQ - later today

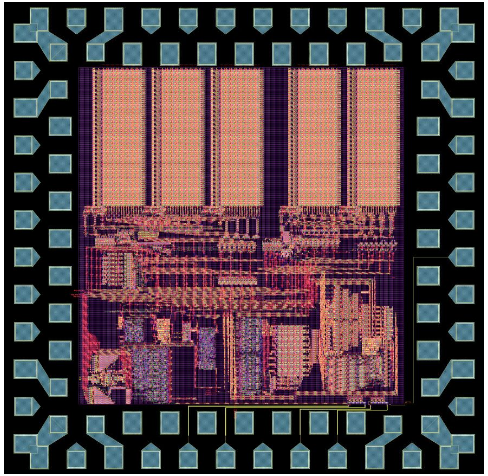
Scaling of SFQ Circuits for mK Integration

- Power:
  - SFQ junctions are typically critically damped
  - $I_c \sim 100\ \mu A$
  - Energy dissipated $\sim \Phi_0 I_c f_{clk} \sim$ 0.2 nW per JJ at 10 GHz
- Size:
  - SFQ tech works at fixed LI_c ~ few flux quanta
  - Maximum reliable I_c density ~ 20 kA/cm^2
- Scaling:
  - Allow fixed power density
  - High I_c: integration limited by max power
  - Low I_c: integration limited by inductor size

8b CLA ca. 2011
Northrop (RQL)
~800 JJ



8b CPU ca. 2016
Northrop (RQL)
~17k JJ



Challenges in Superconductor Circuit Design

- Advantages
  - compact passives
  - Low loss
  - Low power dissipation
  - SFQ pulses - fast and accurate

- Challenges
  - No tunable open circuit
  - Typically low impedance to GND
  - Poor isolation, e.g. connecting to bus
  - Low power handling
  - Flux trapping
  - Foundries

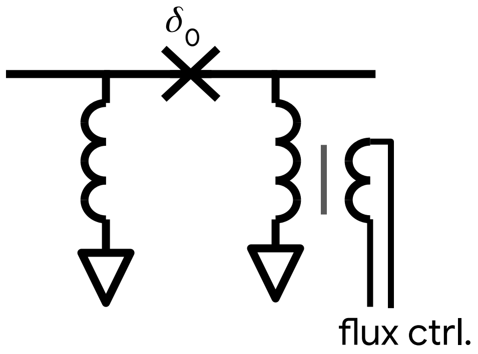
	Semiconductor	**Superconductor**
Wiring	R, C	L, C (transmission lines)
Traps	Charge	Charge + Flux
Voltage / Current	volt, milliamp	microvolt, microamp
Parasitic	skin effect	kinetic inductance
Active device	R_{ON} to open circuit, high Z gate	Inductive, no open circuit, low Z gate

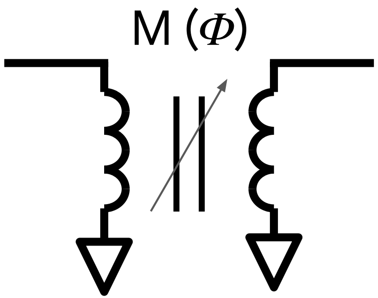
Superconducting IC Design Examples

Microwave Switches for QC - Signal Routing

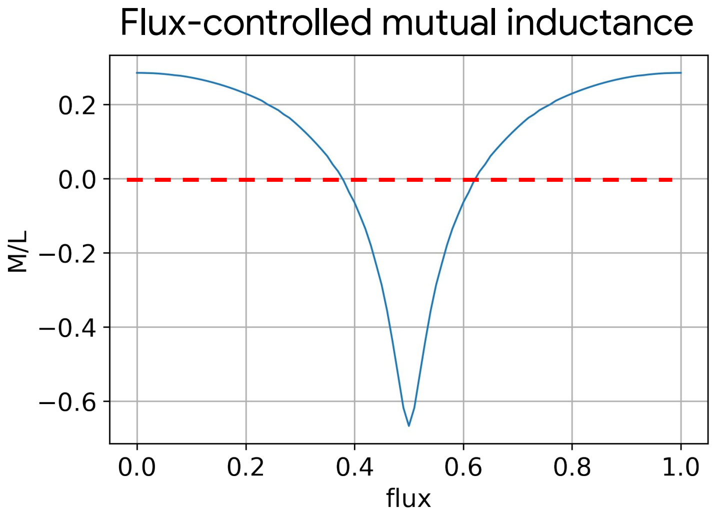
How to implement a microwave switch?

- We don't have a good switchable "open circuit"
- No power dissipation on chip
- Low insertion loss and wide-band





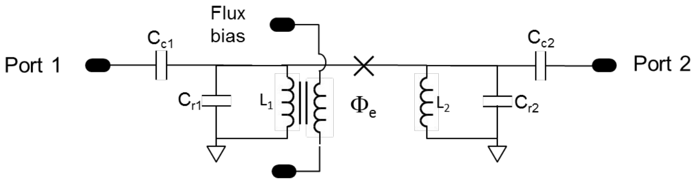
$$\frac{\Phi_0}{2\pi}\delta_0 + LI_c \sin\delta_0 = \Phi$$

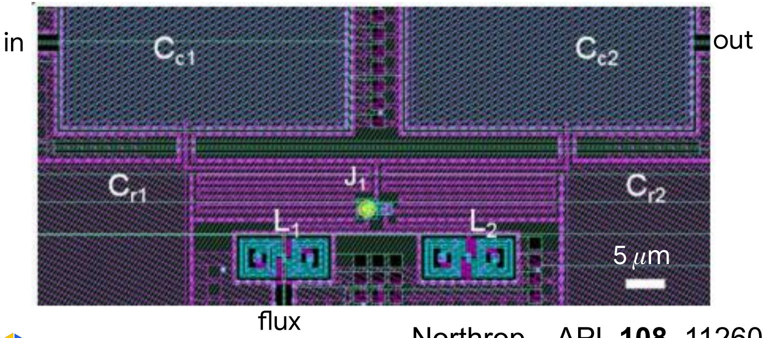


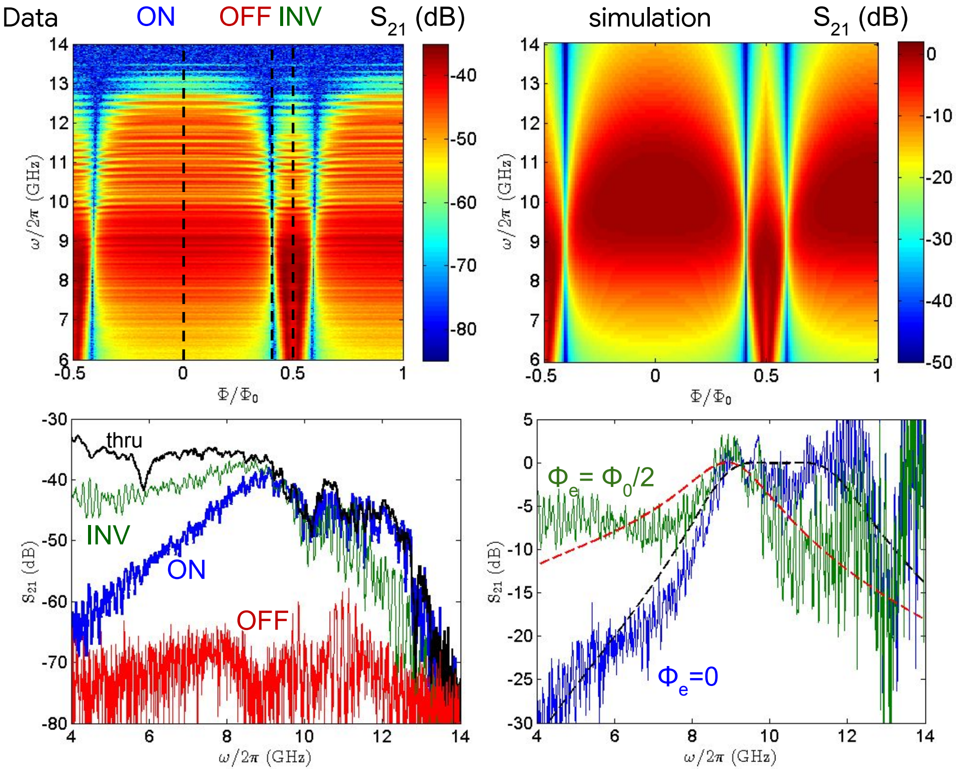
Microwave Switches for QC

How to implement a microwave switch, if active element necessitates inductive shorts to ground?

- Use junction as tunable coupling
- Embed in band-pass network



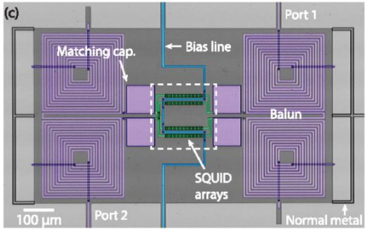




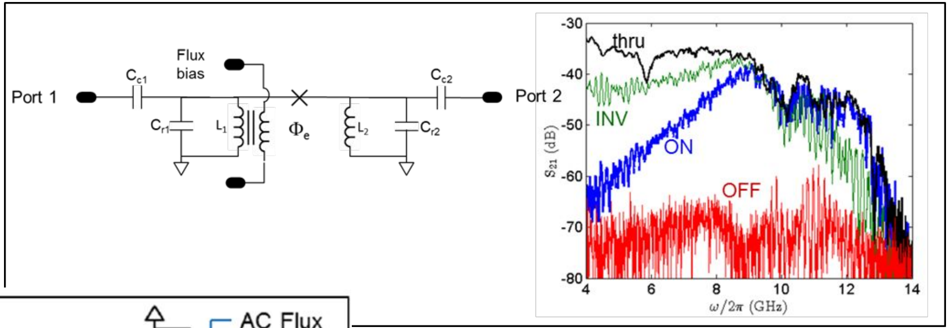
Northrop – APL **108**, 112601 (2016)

Microwave Switches for QC

Single-Pole Single Throw (SPST)

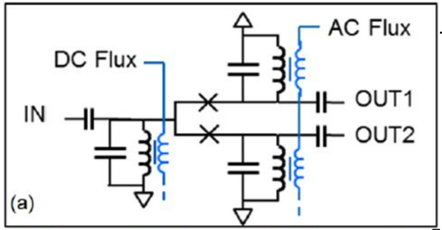


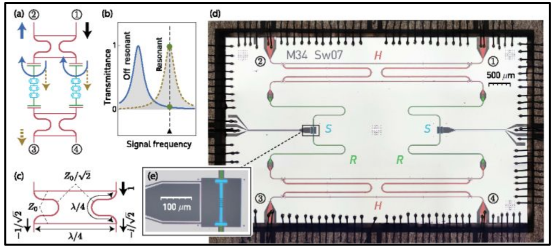
JILA – APL **108**, 222602 (2016)



Northrop – APL **108**, 112601 (2016)

Single-Pole Double Throw (SPDT)

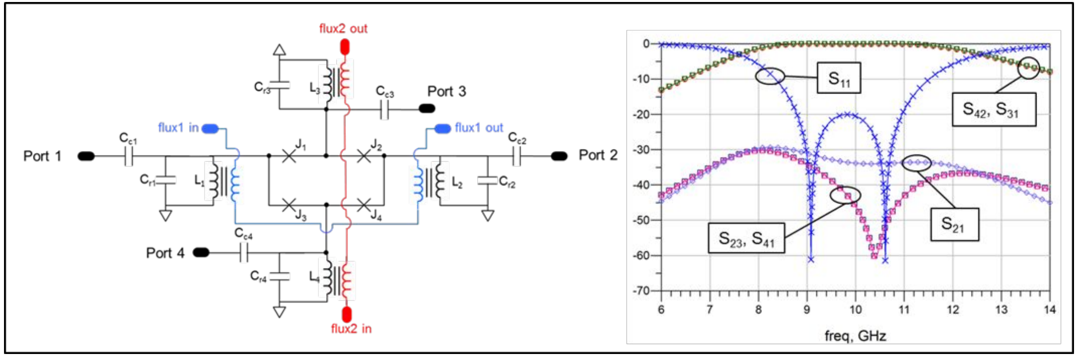




ETH – Phys. Rev. Applied **6**, 024009 (2016)

- ✔ Fast
- ✔ Non dissipative
- ✔ GHz bandwidth
- ✔ Flux control

Double-Pole Double Throw (DPDT) transfer



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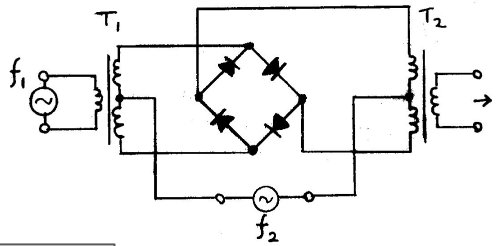
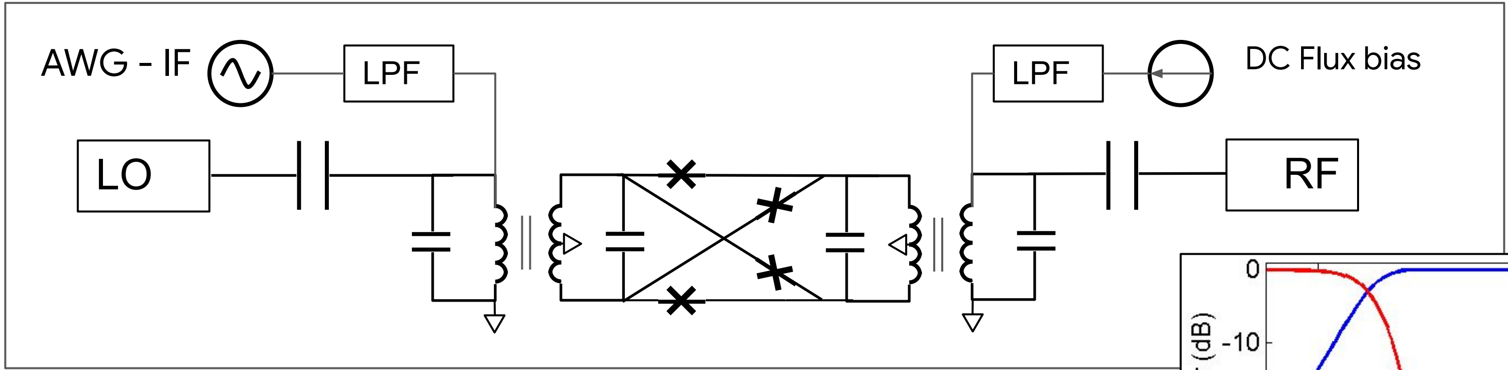
Mixers and Modulators - Control Pulse Shaping

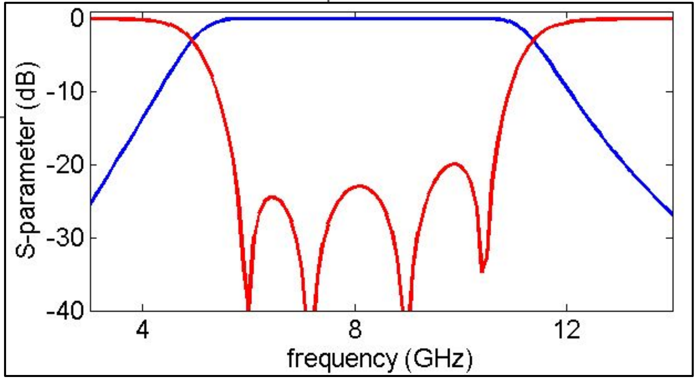
Analog signal processing with a Josephson double-balanced mixer

- Wide-band, no dissipation on chip





Northrop, JAP **121**, 073904 (2017)



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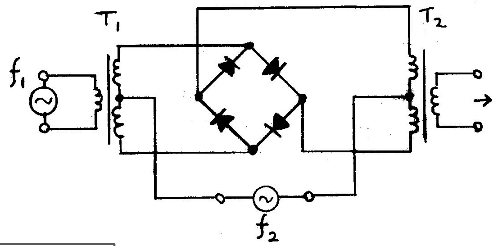
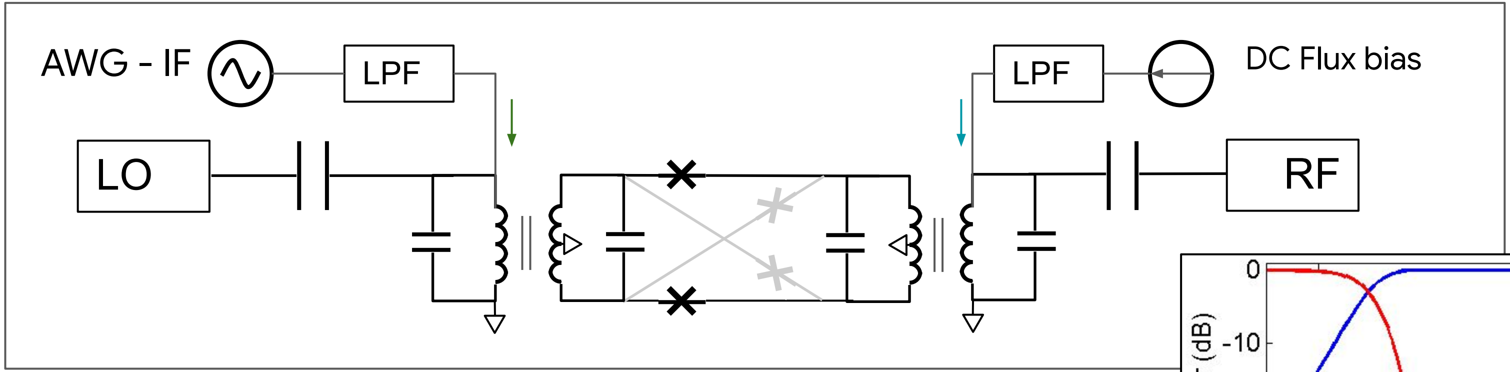
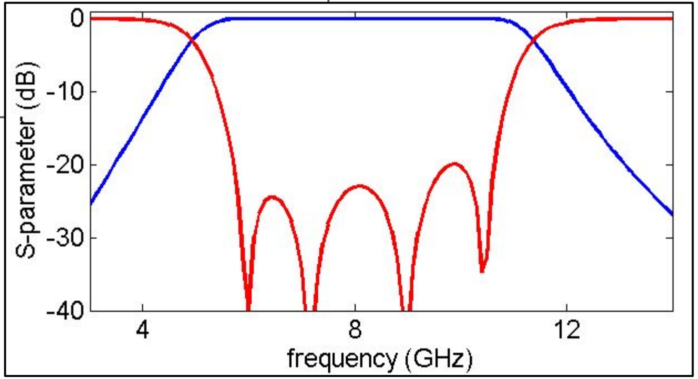




Northrop, JAP **121**, 073904 (2017)



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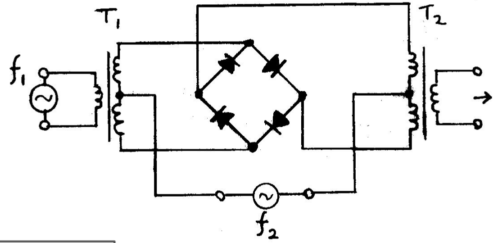

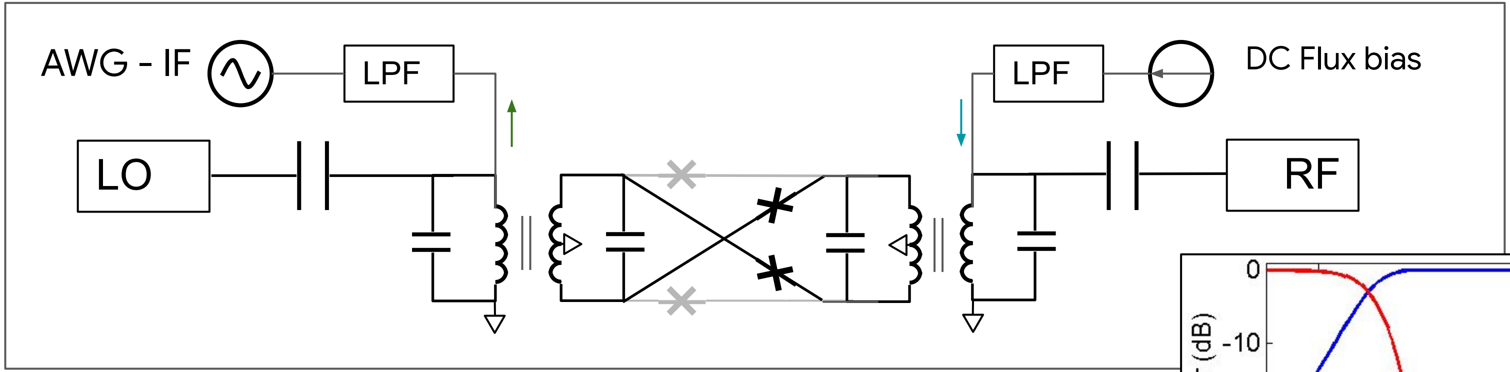

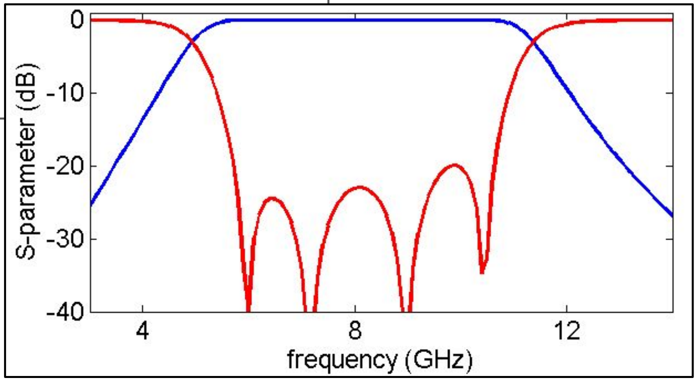

Northrop, JAP **121**, 073904 (2017)

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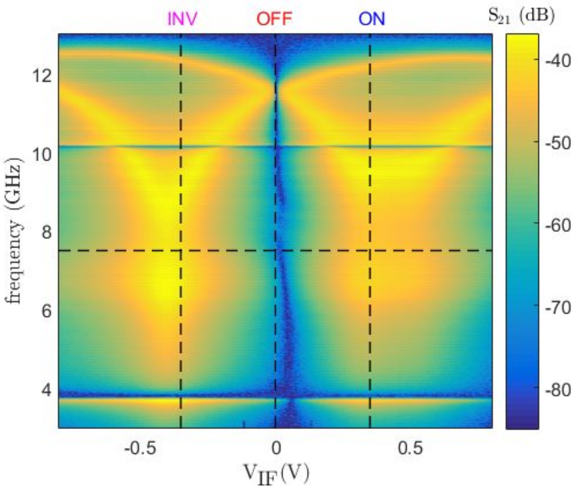
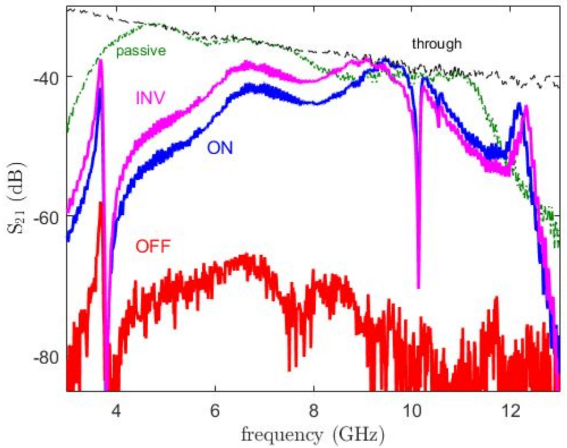
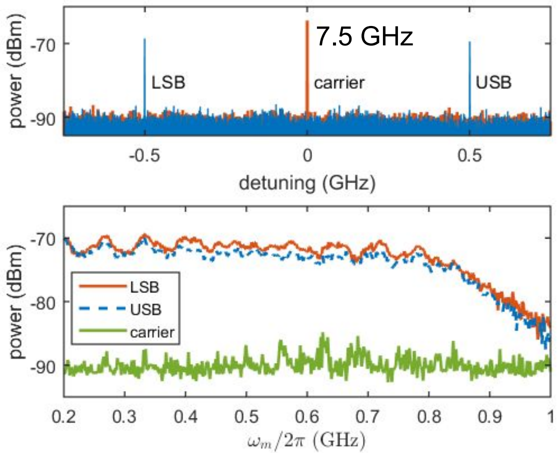
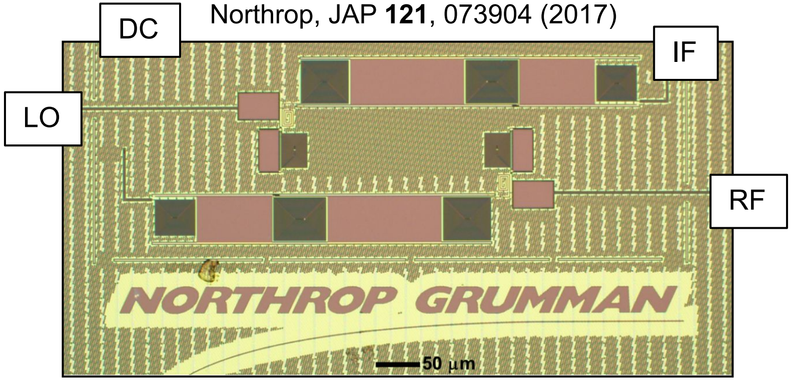








Northrop, JAP **121**, 073904 (2017)

- Use Josephson junctions for tunable coupling
  - Non-dissipative operation
- Embed in band-pass network
  - Deal with shunt inductors, ideally low IL, engineer bandwidth
- SQUID design is important
  - Manage nonlinearity, saturation > 1 nW

Active Superconducting Devices

Needed for qubit readout - amplification & isolation

Signal powers -130 dBm to -120 dBm per qubit

- AC powered
- Josephson junction active elements
- Easy to modulate reactance
- Use parametric amplification and frequency conversion processes
    - Josephson parametric amplifiers
    - Traveling wave parametric amplifiers (next talk!)
    - Parametric circulators
    - Synthetic circulation
- Challenges - bandwidth and saturation power

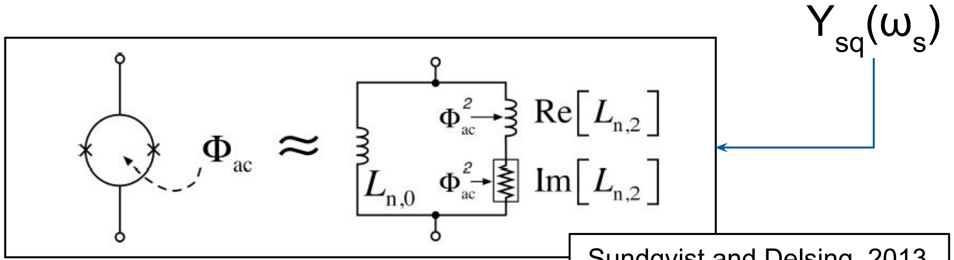
many circulators

Josephson Parametric Amplifiers

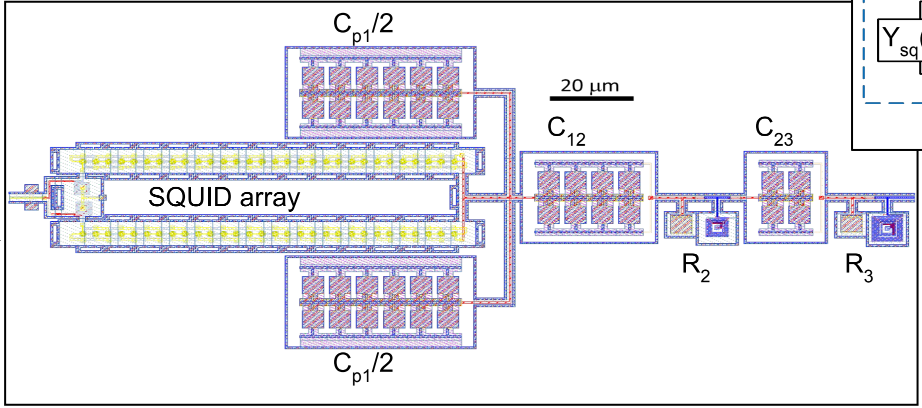
Pump SQUID at twice the signal frequency

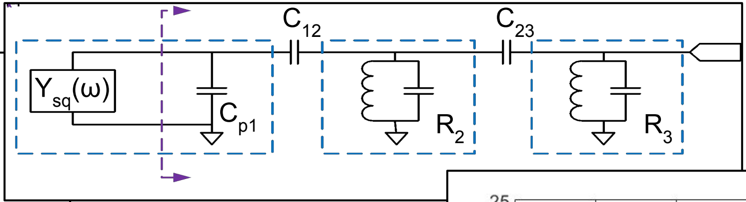
Effective admittance has **negative real** part

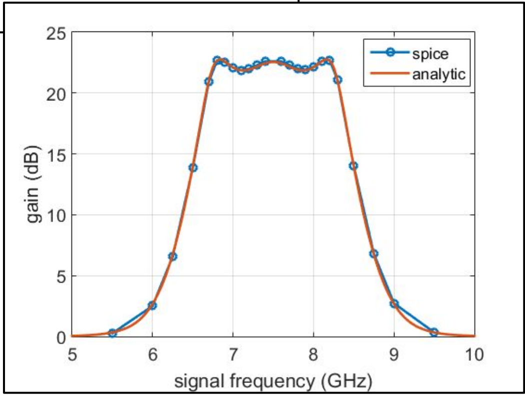
- Band-pass network for impedance match
- SQUID array design for better saturation
- Wide-band reflection gain



Sundqvist and Delsing, 2013





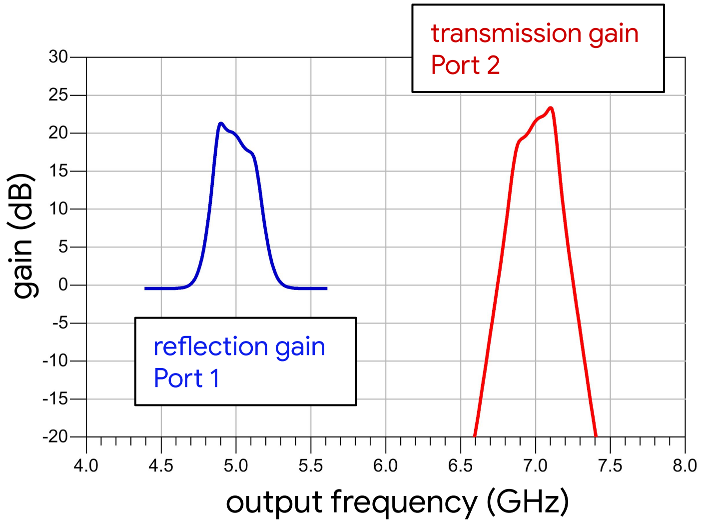


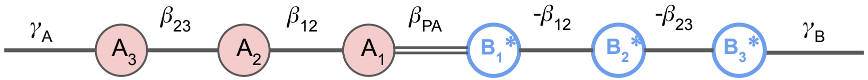
Northrop
arXiv:1711.07549 (2017),
IMS2019

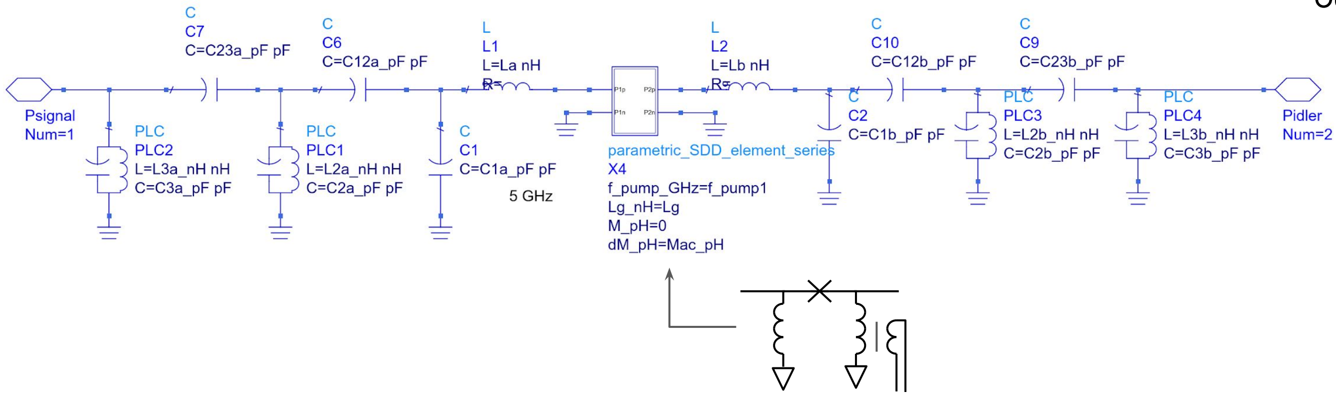
Josephson Parametric Amplifiers

Non-degenerate matched JPA

- Transmission gain
- Frequency converting
- Automated design via filter synthesis methods





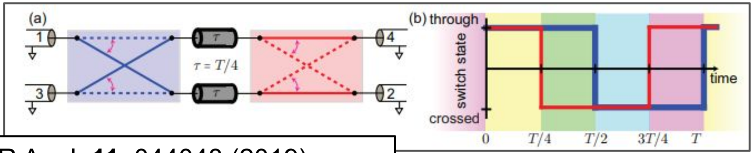


pump @ 2 GHz

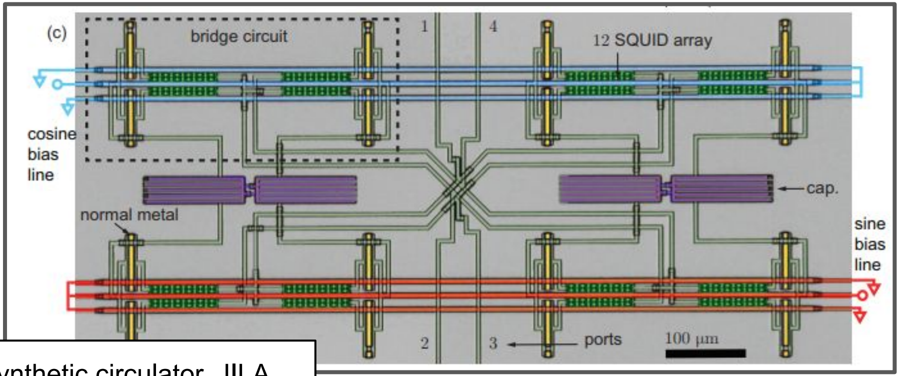
Synthetic and Parametric Circulators

Synthetic circulation

- 2x IQ mixers (or H-bridges) + delay lines
- Low insertion loss, wide band



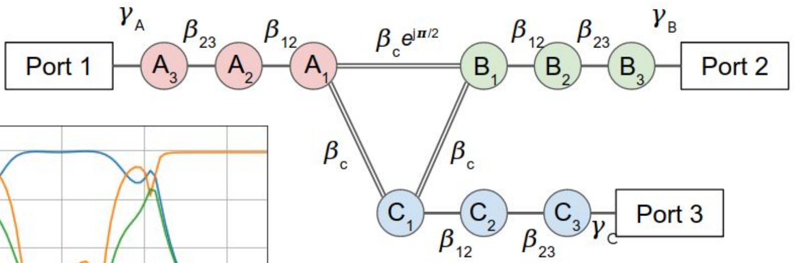
JILA, PR Appl. **11**, 044048 (2019)

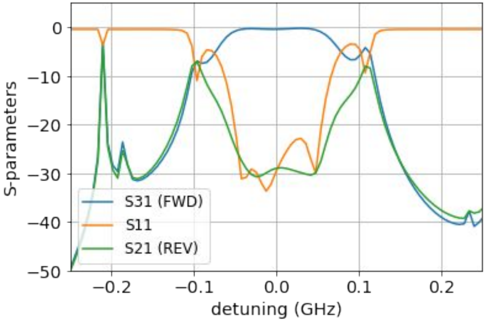


Synthetic circulator, JILA
PRX. **7**, 041403 (2017)

Parametric circulation

- Parametric conversion
- 3 resonant modes share SQUID
- Bandpass matching network





ADS HB simulation

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Conclusion

- Superconducting IC's complement cryo CMOS for qubit control
  - Low power dissipation means we can integrate on the mix-plate
    - Simplify IO requirements
    - Good for signal integrity
  - Low loss superconducting wiring - more compact, efficient passives. Good for microwaves.
- Unique aspects of superconducting IC design
  - Transformers work down to DC
  - No good "open circuit"
  - Typical circuits present low impedance inductive shunts
  - Flux traps
- Low power microwave and mixed-signal devices
  - Switches and modulators
  - Amplifiers and circulators